Factors Controlling the Formation of Fossiliferous Beds in the Devonian Columbus Limestone at Marblehead Quarry, Marblehead, Ohio[1]

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ABSTRACT. This study uses taphonomic, sedimentologic, and stratigraphic evidence from fossiliferous beds in Marblehead Quarry to review two hypotheses: 1) that the fossiliferous beds at Marblehead Quarry represent a series of *in situ* paleocommunities, and 2) whether fossiliferous concentrations in carbonate environments are primarily caused by periods of low net sedimentation. The fossiliferous beds of Marblehead were relatively coarse grained, had a sharp basal contact, and contained fossil assemblages distinct from those within the fossil-poor intervals. Bed 1 was an amalgamation of three fining-upward sequences and contained relatively poorly-preserved fossils, while Beds 2-4 were thin, laterally persistent, and had well-preserved fossil assemblages. Bed 1 is interpreted as containing autochthonous assemblages during a period of increased current energy, but Beds 2-4 are interpreted as tempestites (i.e., rapidly deposited during storm events), and contain allochthonous fossil assemblages. Therefore, hypothesis 1 was partially disproved: Bed 1 and the fossil-poor intervals may represent *in situ* paleocommunities, but Beds 2-4 do not. Furthermore, Beds 2-4 provide an example of fossil concentrations that formed during periods of high net sedimentation, and do not fit the net sedimentation model of hypothesis 2. Nevertheless, sedimentation rate, whether high or low, appears to be the primary factor controlling the formation of fossil concentrations in the Columbus Limestone.

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INTRODUCTION

Paleontologists have traditionally collected specimens from areas of high fossil abundances because of the relative ease of collection and because more paleoecological information may be gained from diverse fossil assemblages than from isolated individuals. It is therefore vital to understand which processes favor the formation of fossil concentrations and how these may affect the constituent fossils.

Three factors, broadly defined, will favor the formation of high concentrations of fossils: low net sedimentation rates, high fossil hardpart production, and diagenesis of the sediment matrix (Kidwell et al. 1986). Kidwell (1986) has proposed that the net sedimentation rate is the primary determinant of whether a fossil concentration will form. Low net sedimentation rates can arise from sediment starvation or dynamic bypassing, or from negative sedimentation rates (i.e., erosion) and can cause a deposit to become relatively enriched in fossil hardparts as finer particles either do not settle out or are selectively removed by winnowing. Under the net sedimentation model, the rate of biologic productivity, and the consequent production of fossil hardparts, is believed to be of secondary importance (Kidwell 1986).

The net sedimentation model was explicitly designed for clastic sedimentation regimes, and is supported by evidence from the Miocene Calvert and Choptank formations of Maryland, both of which represent clastic-dominated marine shelf facies (Kidwell 1986). In a clastic sedimentation regime, sedimentation rates may indirectly influence species abundance, but hardpart production and net sedimentation rate may on the first order be assumed to be independent of one another. In a carbonate environment, however, one can no longer assume sedimentation rate and hardpart production to be independent because increased hardpart production should provide more carbonate source material, directly leading to increased sedimentation rates.

The present study tested the applicability of the net sedimentation model to carbonate environments by examining the Marblehead Member of the Devonian Columbus Limestone, exposed at Marblehead Quarry, Marblehead, OH. The net sedimentation model predicts that discontinuity surfaces, as evidence of erosion or low net sedimentation, should be associated with most fossil concentrations, and that fossils will decrease in abundance away from such surfaces (Kidwell 1986). Therefore, if the net sedimentation model holds, it should be possible to find erosion or omission surfaces in association with the majority of the fossil assemblages at Marblehead. The sedimentary, stratigraphic, and taphonomic evidence gathered to test the net sedimentation model was further used to evaluate the hypothesis that the fossil concentrations at Marblehead Quarry represent a succession of *in situ* paleocommunities (Frank unpubl. thesis 1981).

MATERIALS AND METHODS

The Columbus Formation is a highly fossiliferous limestone deposited during the Middle Devonian. The Columbus was later subdivided into the Venice, Marblehead, and Bellepoint members on the basis of lithology and biostratigraphy (Swartz 1907). In northern Ohio the Columbus Limestone comformably overlies the Lucas Formation of the Detroit River Group and underlies the Delaware Formation (Fig. 1). Based upon

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lithology and fossil evidence, Chapel (unpubl. Ph.D. thesis 1975) interpreted the Columbus to represent a shallow marine carbonate platform, existing at or below wave base.

Marblehead Quarry is located near Lake Erie, near the towns of Sandusky and Port Clinton (Fig. 2). Long known for diverse fossil assemblages, the Columbus Limestone quarries on the Marblehead peninsula have been a classic area for paleontologists seeking to describe the Devonian fauna of northern Ohio (Frank unpubl. thesis 1981, Chapel unpubl. thesis 1975, Cooper 1957, Kerr unpubl. Master's thesis 1950, Stauffer 1909, Swartz 1907). Frank most recently performed a detailed study of the paleoecology and diagenesis of the Marblehead Member at Marblehead Quarry, and concluded that it records a successional sequence of nine *in situ* paleocommunities.

The present study was confined to the inactive part of the quarry, east of Alexander Pike (Fig. 2). About four meters of vertical section are exposed on the quarry walls, upon which most field observations were made (Table 1). The volume percentage occupied by fossils was estimated using the visual aids of Chilingar and Terry (1955). Taphonomic data were obtained by randomly choosing a spot within a bed and recording the appropriate characteristics of up to 50 nearby individuals. Quantitative estimates were derived for fossil size, percent of articulated individuals, and the percent of individuals in life position. Fragmentation and abrasion were qualitatively recorded as low (fragments rare/<20% showing significant abrasion), moderate (whole individuals uncommon/20-80% of fossils showing significant abrasion), or high (only robust species are whole/>80% of fossils showing significant abrasion). The size of matrix grains and their sorting were estimated using a standard visual aid.

RESULTS

In Marblehead Quarry, the Columbus Limestone consists of alternating fossil-rich packstones and fossil-poor wackestones (Fig. 3). The matrix was composed of disassociated crinoid ossicles, small shell fragments, and other small grains rendered unidentifiable by recrystallization. The fossil-poor and fossil-rich intervals differed in fossil composition; fossil-rich assemblages contained mostly rugose corals and strophomenid brachiopods, whereas fossil-poor intervals were dominated by brachiopods but also contained significant numbers of colonial corals in life position (i.e., with upward-pointing calyxes). Four distinct fossil concentrations were present, each consisting of laterally extensive and moderately well-sorted beds ranging in thickness from 2 to 49 cm (Table 1). All four had a scoured basal contact (Fig. 4), but only Bed 1 showed any internal sedimentary structures.

Bed 1 was an amalgamation of three fining-upward sequences, and was the most complex of the fossiliferous beds (Fig. 3). The sequences ranged from 12 to 22 cm

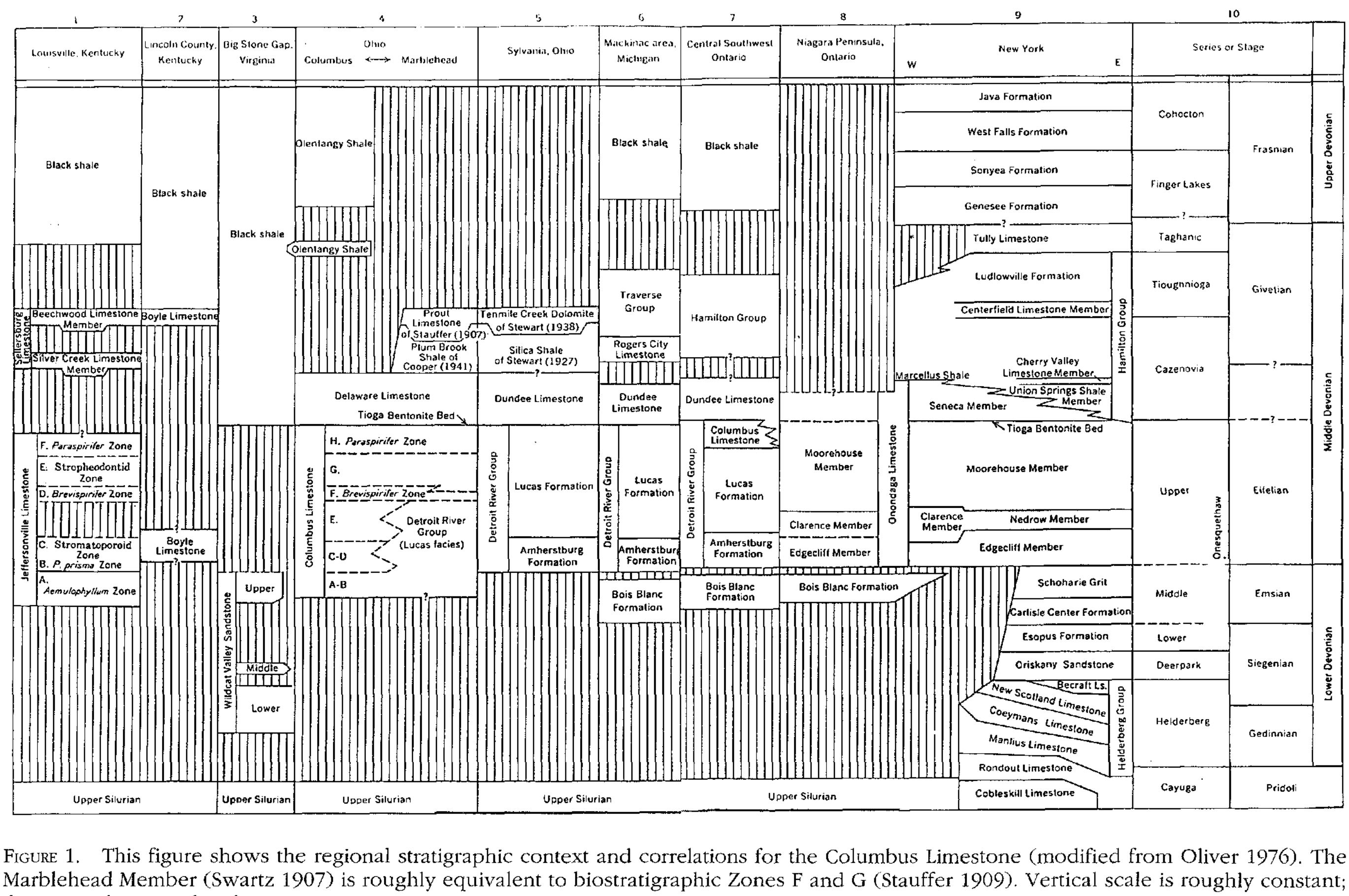

FIGURE 1. This figure shows the regional stratigraphic context and correlations for the Columbus Limestone (modified from Oliver 1976). The Marblehead Member (Swartz 1907) is roughly equivalent to biostratigraphic Zones F and G (Stauffer 1909). Vertical scale is roughly constant; there is no horizontal scale.

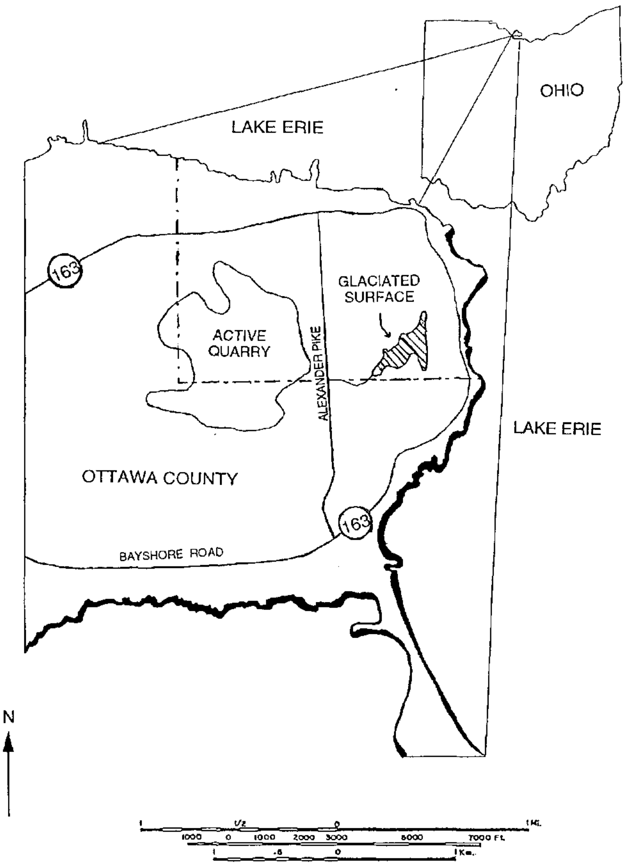

FIGURE 2. Map showing the location of the Marblehead Quarry study site. All observations were made around the glaciated surface. (Modified from Frank unpubl. thesis 1981).

in thickness, each truncated by the one above. Brachiopods predominated, but rare specimens of bryozoans, rugose corals, colonial corals, and a single porifera were also found. The percent of Bed 1 occupied by fossils varied from 5 to 40%, while sorting of the bioclasts was good (Table 1). The degree of fragmentation increased as grain size decreased, from whole fossils within the basal shell lags up to unrecognizable shell fragments. On average, less than 10% of the brachiopods were articulated, while of the 27 brachiopod valves counted in Bed 1, all but two were concave-down.

Bed 2 was a 7 cm thick packstone with a poorly sorted matrix of angular to subangular grains (Table 1). Bed 2 extended across the quarry, and had a particularly prominent basal contact (Fig. 4). The fossil assemblage of Bed 2 was dominated by strophomenid brachiopods, with spiriferid brachiopods and rugose corals occurring in minor proportions, and was defined as the Strophomenacea-Paraspirifer community by Frank (unpubl. thesis 1981). The strophomenid brachiopods showed relatively little variation in size, ranging from 3 to 5 cm. Fossils were loosely packed, were matrix supported, and occupied about 40% of the bed's volume. Few brachiopods were articulated, but there was little fragmentation or abrasion. No clear preferred orientation existed for the brachiopods or rugose corals in this bed.

Bed 3 consisted of a series of discontinuous lenses with maximum thickness of 4 cm. Of the fossiliferous beds, it is the only one not traceable across the entire quarry. In other respects, including lithology, faunal composition, and taphonomy, Bed 3 was similar to Bed 4.

Bed 4, a packstone, was easily traceable across the quarry because of its high concentration of rugose corals and, along with Bed 3, was defined as the Rugosan Community (Frank unpubl. thesis 1981). The sharp basal contact of Bed 4 truncated a number of vertical burrows into which matrix from Bed 4 had passively filled. Bed 4 was bioclast supported and had a fossil density up to 60% of volume. Fossils were well preserved. Some fragmentation and disarticulation had occurred, but approximately 40% of the brachiopods remained articulated and showed little abrasion (Table 1). Both rugose corals and brachiopods were uniform in size, ranging from 2 to 3 cm. Nearly half of the rugose corals were recumbent with their calyxes oriented downward, whereas two-thirds of the brachiopods were at high angles to bedding. Geopetal structures, consisting of sparry, void-filling carbonate cements, occurred beneath several concave-down brachiopods.

In summary, the fossil-rich and fossil-poor beds were distinct in not just relative fossil abundance, but also in their sedimentology, taphonomy, and faunal composition. The fossil-poor beds contained a relatively fine matrix (mudstone-wackestone), and were each sharply truncated by overlying fossil-rich beds. Different faunal assemblages were characteristic of the fossil-poor and fossil-rich beds. For example, colonial corals were more prevalent in the fossil-poor intervals. Among the fossiliferous beds, Bed 1 was sedimentologically and taphonomically distinct from Beds 2-4. Bed 1, an amalgamated fossil concentration, contained three sequences fining upward from an erosive basal contact through a shell lag to wackestone. Fragmentation in Bed 1 was moderate to high, articulated shells were rare, and disarticulated brachiopod valves strongly preferred a

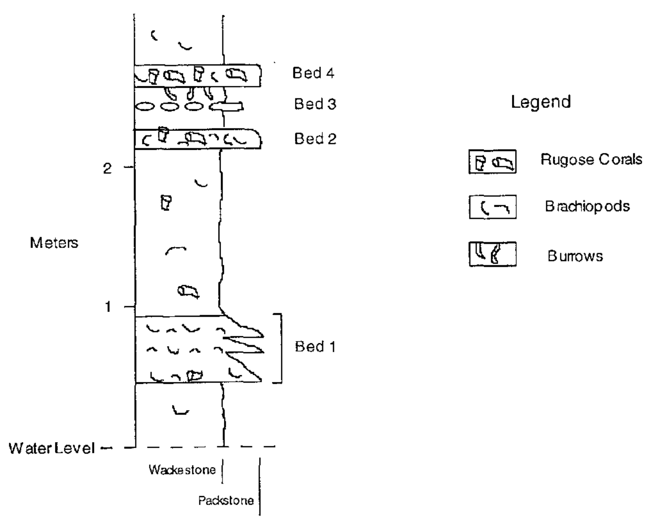

FIGURE 3. A stratigraphic section of the quarry walls surrounding the inactive quarry. The alternation of fossil-rich and fossil-poor beds corresponds with changes in grain size.

TABLE 1

Sedimentologic and taphonomic data from the Marblehead Member of the Columbus Limestone at Marblehead Quarry.

Lithology	Bed 1 Wackestone/Packstone	Bed 2 Packstone	Bed 3 Packstone	Bed 4 Packstone
Laterally Extensive	n.d.	yes	no	yes
Thickness (cm)	49	7	2	6
Sharp Basal Contact	yes	yes	yes	yes
# Fining Upward Sequences	3	0	0	0
Sorting	well sorted	poor	well	well
Articulation	10%	n.d.	<5%	40%
Fragmentation	varies	moderate	high	low
Abrasion	varies	low	moderate	low
Rugose Orientation*				
Up	n.d.	33%	61%	54%
Down	n.d.	29%	8%	23%
Side	n.d.	38%	31%	23%
Brachiopod Orientation**				
Concave-Up	7.5%	40%	n.d.	33%
Concave-Down	92.5%	60%	n.d.	67%

n.d. = not determined
*Rugose Orientation refers to the orientation of the calyx of a rugose coral.
**Brachiopod Orientation was measured only for disarticulated valves.

concave down orientation. Beds 2-4 were all packstones with no visible internal sedimentary structures. Though relatively thin (<10 cm), Beds 2 and 4 were laterally persistent. Fossils were evenly dispersed throughout Beds 2-4, fragmentation was low to moderate, encrustation and bioabrasion was low, and articulated brachiopods were present. Most of the undamaged fossils in Beds 2-4 did not appear to be in life position.

DISCUSSION

The above evidence leads to a modification of the hypothesis that the faunal assemblages of Marblehead Quarry represent *in situ* paleocommunities (Frank unpubl. thesis 1981). It is likely instead that while Bed 1 and the relatively fossil-poor intervals are *in situ* paleocommunities, Beds 2-4 represent allochthonous assemblages transported during storm events. The fossil-poor intervals, with their relatively fine matrix and colonial corals in life position, are interpreted as having been deposited in a shallow marine, below wave-base environment, as is consistent with previous interpretations (Chapel unpubl. thesis 1975, Frank unpubl. thesis 1981). The fossiliferous beds, with their coarser matrix and richer fossil assemblages, most likely represent either: 1) paleocommunities adapted to relatively high energy conditions, or 2) periods of rapid deposition (i.e., a tempestite or turbidite). Taphonomic evidence indicating the duration of exposure of fossils is the primary means for choosing between these scenarios (Brett and Baird 1986).

Bed 1 may mark a relatively lengthy time of increased hydraulic energy, reflecting perhaps a slight lowering of wave base, and the fossil assemblages within these beds probably represent *in situ* paleocommunities. Increased exposure of fossils in Bed 1 is suggested by the high degree of fragmentation and abrasion found in the upper

FIGURE 4. Photograph of Bed 3 showing an erosional basal contact typical of the fossiliferous beds. Scale = 10 cm.

level of each fining-upward sequence. The concave-down preferred orientation of the disarticulated brachiopod valves also suggests the valves were exposed long enough to be reoriented by currents into a stable position.

Beds 2-4, however, were not deposited gradually, but are interpreted as having been deposited rapidly, over a period of hours or days. The broad lateral extent of Beds 2-4, their coarse matrix, and their sharp basal contacts are characteristic of tempestites (Aigner 1985, Brenner et al. 1985, Morton 1988), and the geopetal structures of Bed 4 suggest a rapid burial that left voids beneath overturned brachiopod valves. Although a rapid deposition is also characteristic of turbidites, the flatness of the Devonian sea floor in Ohio (Chapel unpubl. thesis 1975) makes turbidity currents unlikely.

A rapid burial of the fossils in Beds 2-4 is further indicated by the taphonomic evidence, in particular by the low levels of encrustation and disarticulation. One would expect fairly high levels of encrustation and disarticulation if these fossils had been exposed for a prolonged period of time to medium- or high-energy environments. The fossils have been moderately fragmented, which is suggestive of some period of exposure, but fragmentation may have occurred prior to storm transport and burial (Brett and Baird 1986). Furthermore, the lack of a significant preferred orientation of the fossils suggests a rapid deposition and burial.

If the beds are in fact tempestites, then the fossils must represent allochthonous assemblages since they are distinct enough from the fossil assemblages of the fossil-poor beds to rule out a local recycling of fossils. Indeed, transport of fossil assemblages was not uncommon during the deposition of the Columbus Limestone (Chapel unpubl. thesis 1975).

Does the net sedimentation model apply to carbonate environments? In a carbonate regime, the fragmentation and abrasion of fossil hardparts will be the primary source of sediment, implying that sedimentation rates are not independent of rates of hardpart production. According to the net sedimentation model, fossil concentrations form when net deposition of sediments is low (Kidwell 1986, Kidwell et al. 1986), which leads to the prediction that most fossils will be associated with discontinuity surfaces and fossils should decrease in abundance away from the discontinuity.

The prediction of fossils associated with discontinuity surfaces is only partially confirmed by the fossil concentrations at Marblehead Quarry. Bed 1 corresponds well to the net sedimentation model as it contains three discontinuity surfaces, each immediately followed by a shell lag. However, while Beds 2-4 have basal discontinuity surfaces, their fossils are evenly dispersed with no relation to the discontinuities. As discussed above, Beds 2-4 are interpreted as having formed during storm events, i.e., during short periods of high sedimentation rates. These beds therefore do not follow the prediction of the net sedimentation model that fossil concentrations are primarily engendered during times of low net sedimentation. However, sedimentary processes are directly responsible for Beds 2-4, because their fossils presumably were concentrated by a winnowing away of finer particles during storm transport and deposition. Changes in the rate of hardpart production do not appear to have had much influence on the formation of these beds. The fossil-rich tempestites of Marblehead Quarry thus provide an example of fossil concentrations that did not form during periods of low net sedimentation. Nevertheless, for both clastic and carbonate depositional environments, sedimentation, not biologic productivity, is the dominant factor controlling the presence or absence of fossil concentrations.

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